Cosmic Chemistry: Cosmogony

Doppler Effect—Are You Coming or Going?

STUDENT TEXT

The Doppler effect, discovered by the Austrian scientist Christian Doppler in the 19th century, is a phenomenon of fundamental importance to astronomers, although it finds applications in more mundane areas as well. It applies to wave motion—sound waves, light waves, or even waves on water. You have experienced the consequences of the Doppler effect if you have ever listened carefully to the sound of a siren or high-pitched racecar engine as it approaches and then recedes from you. You will have noted that the pitch (frequency) of the sound increases as the source of the sound approaches you and then decreases as source moves away.

Christian Doppler

The physics behind this is easy to understand. Sound consists of a series of traveling compressions and rarefactions of air pressure, which the physicists call longitudinal or compressional waves. When the compressions (wave crests) impact on your eardrums, they are perceived by your auditory nerves and a message is sent to your brain that you interpret as sound. The more closely spaced the wave crests, the higher the sound frequency and vice-versa. Carefully distinguish between pitch and loudness. Pitch has to do with the frequency with which the wave crests hit your eardrums, and loudness is a physiological response that has to do with how hard the wave crests bang into your eardrums.

As a sound source approaches, the waves ahead of the source get shoved together, giving rise to an apparent increase in frequency or a higher pitch as the intervals between wave crests diminish. As the sound source moves away, the waves are farther apart and the sound drops in pitch. These are called Doppler shifts.

Note that the same phenomenon would apply if a stationary source was emitting a sound and you were moving quickly toward the source. Because of your motion, the frequency with which your eardrums encounter a wave crest would increase, and the apparent pitch of the sound would increase. If you were moving away from the source, the frequency would decrease.

The ideas above may be expressed mathematically and exact calculations of apparent pitch can be calculated.

The mathematical relationships describing the Doppler shifts for sound are as follows:

For a moving source:
$F_2 = F_1 \left| V/(V \pm v_s) \right|$ where F_2 is the apparent or observed frequency, F_1 is the true frequency of the sound source, V is the speed of sound, and v_s is the speed of the source. Use the negative sign if the source is moving toward the observer and a positive sign if the source is moving away.

For a moving observer:
$F_2 = F_1 [(V \pm v_o)/V]$, where F_2, F_1, and V have the same meaning as above, v_o is the speed of the observer and the negative sign applies if the observer is receding from the source.

Scientists have learned that electromagnetic radiation emitted by a moving object also exhibits a Doppler effect highly comparable to that observed for sound. After all, electromagnetic radiation is just another wave phenomenon. Electromagnetic waves moving toward an observer are squeezed together, their frequency appears to increase, and is therefore said to be "blue shifted." Similarly, if an object is moving away from an observer, light emitted by the object is stretched, the frequency decreases, and is said to be "red shifted." Doppler shifts of radiation emitted by stars and other celestial objects are invaluable in determining the movement of the objects with respect to our location in space. Historically, most astronomical research involved visible light, but today, virtually all parts of the electromagnetic spectrum are used to investigate Doppler effects. Because of the inverse relationship between frequency and wavelength of light (remember $f = \nu/\lambda$, where f, ν, and λ represent frequency, the velocity of light, and wavelength, respectively), we can describe the
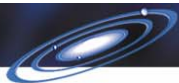
Doppler shift for light in terms of wavelength instead of frequency. Radiation is blue shifted when its wavelength decreases, and red shifted when its wavelength increases. That is to say, if an object is receding, the wavelength is shifted to a higher value, a red shift. If an object is approaching, the wavelength shifts to a lower value, a blue shift. In astronomy, scientists refer to longer-wavelength radiation as "redder" and shorter-wavelength radiation as "bluer," than the original spectral line. The terms "red shift" and "blue shift" do not relate to actual colors except for the very narrow visible part of the spectrum.

Astronomers can use red shifts and blue shifts to calculate exactly how fast stars and other objects move toward and away from Earth. An oft-quoted example involves the spectral lines (i.e. light) emitted by hydrogen gas in distant galaxies *[see Cosmic Chemistry, Sun and Solar Wind]*. An important spectral emission line for hydrogen is found in labs here on Earth at a wavelength of 21 cm. The 21 cm line is the spectral position of the line, or a measure of the energy the photons have. If a cosmic source of hydrogen emits this spectral line and it is subsequently observed at 21.1 cm on Earth, we would call this a red shift of 0.1 cm. This shift would indicate that the source is moving away from us at more than 1,400 kilometers per second.

The mathematical relationship that applies is:
$V_o = (\Delta_\lambda/\lambda)c$, where V_o is the velocity of the light source, λ is the wavelength if the source were standing still (i.e. the wavelength at the source), Δ_λ is the change in wavelength arising from the motion of the source, and c is the velocity of light.

This equation assumes that the velocity of the source is much less than the velocity of light. Also, note that, unlike the Doppler shift for sound, it does not matter whether the observer or the source is in motion. One needs to know only their relative velocities. It should be mentioned here that shifts in wavelength can arise not only from relative motion. Two other phenomena can come into play, both arising from Einstein's general theory of relativity. The first is the Gravitational Redshift that is associated with strong gravitational fields. The other is the Cosmological Redshift, which arises from the stretching of space subsequent to the Big Bang. Most stellar objects are red shifted, implying that the universe is expanding.